Island Universes

Returning to XIX Century

- By the end of XIX century most astronomers believed that:
  - The Milky Way (galaxy) was small (about 2 kpc across), as Herschel found.
  - In addition to stars, space contained "nebulae". Small spiral nebulae were by far the most common kind of nebulae.
  - All nebulae were glowing blobs of gas.
- Most physicists believed that the universe was infinite in space and time and more-or-less uniformly filled with stars.
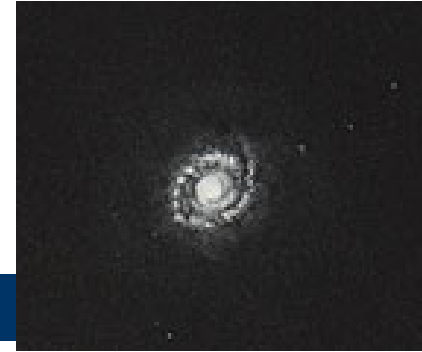
Sky Photography in 1900
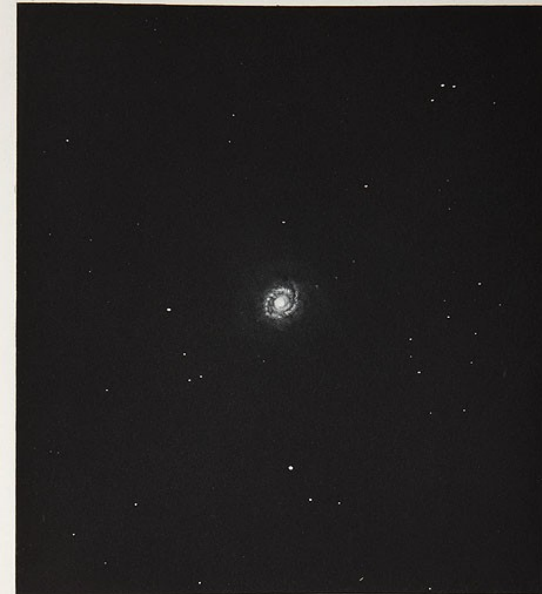

The Great Nebula in Adromeda

The Great Nebula in Orion

The Spiral Nebula M94. Canum Venaticorum

Doppler Effect

- Christian Doppler (1803 – 1853) is the Evil Genius of all sensible drivers.

- In 1842 he discovered the Doppler effect: a shift in the frequency (wavelength) of a wave emitted or reflected by a moving source.

60 miles an hour?! But that's impossible! I've only been driving for 15 minutes!

Outgoing waves

Radar gun

Reflected waves (higher frequency)

Radar gun
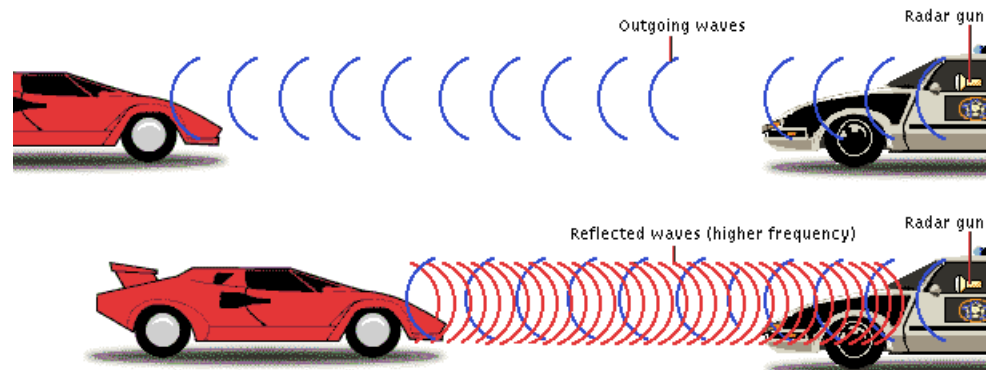
Doppler Effect II

- Doppler effect is measured by **redshift:**

$$z = \frac{\lambda_{\text{RECEIVED}} - \lambda_{\text{EMITTED}}}{\lambda_{\text{EMITTED}}}$$
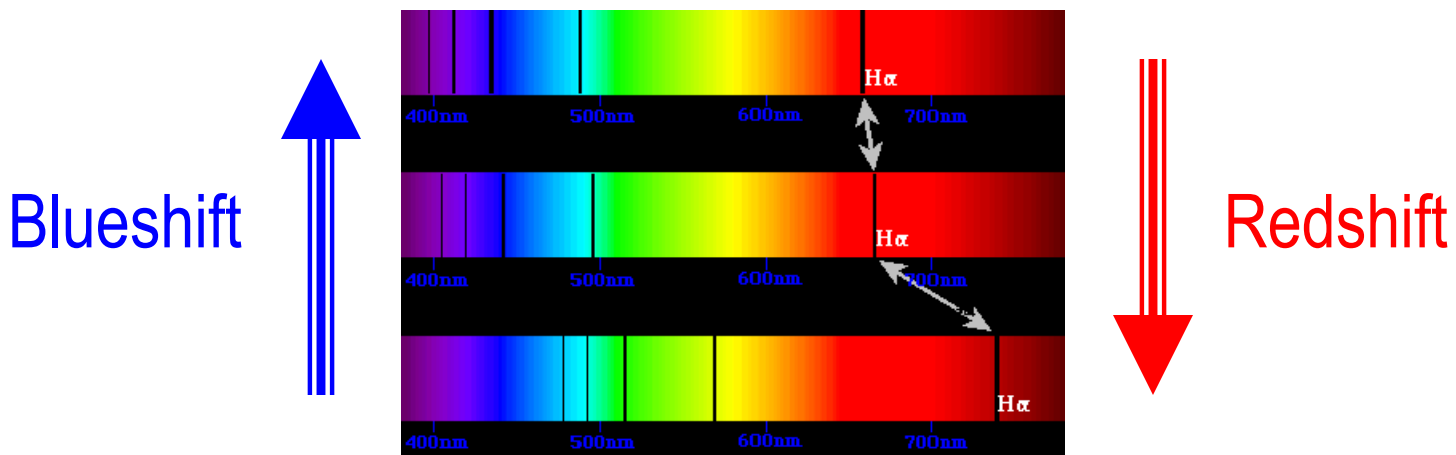
- *Observed* redshift is determined by the **line-of-sight** velocity of a source of wave:

$$z = \frac{v}{c}$$

- It tells nothing about a **tangential** (sideways) velocity.

Dopler Effect III

- If the source is receding, the redshift **z** is positive (proper **redshift**).
- If the source is approaching, the redshift **z** is negative – **blueshift**.


Blueshift

Redshift

Vesto Slipher (1887 – 1969)

- In 1912 - 1917 he measured Doppler redshifts for some of the spiral nebulae. He found that many of them have velocities much larger than the velocities of stars in the Milky Way.

- He found that out of 25 nebulae, 21 were redshifted, moving away from the Sun. He paid no attention to that fact.

- He suggested that they were "stellar systems seen at great distances".

A Battle for Galaxies: Attack

- In 1917 Heber Curtis (1872 – 1942) discovered three faint *novae* in Andromeda Nebula. From that he was able to conclude that Andromeda Nebula was about 200 kpc away.

- "Way too far", said the others.

- He was too short by a factor of 4.
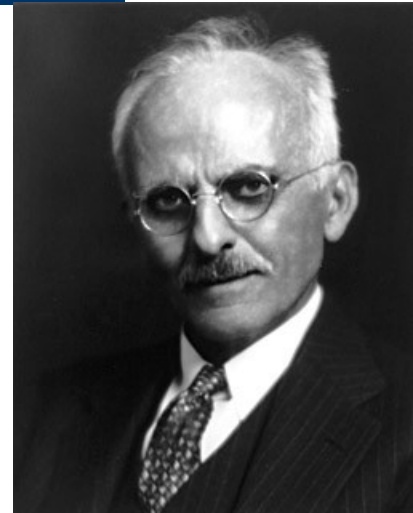
A Battle for Galaxies: Defense

- In 1916 Adriaan van Maanen (1884 – 1926) from the Mount Wilson Observatory (near LA) directly observed the rotational motion of the spiral nebula M100.

- He was a highly respected observer, everyone believed him.

- That was the death blow to the island-universe hypothesis.

Harlow Shapley (1885 – 1962)

- At the same time Harlow Shapley from the same Mount Wilson Observatory measured the size of the Milky Way using **_globular clusters_**. He found that the Milky Way is about 100 kpc in size – 20 times the size of Herschel's – Kapteyn's model.

- He was off by a factor of 3.
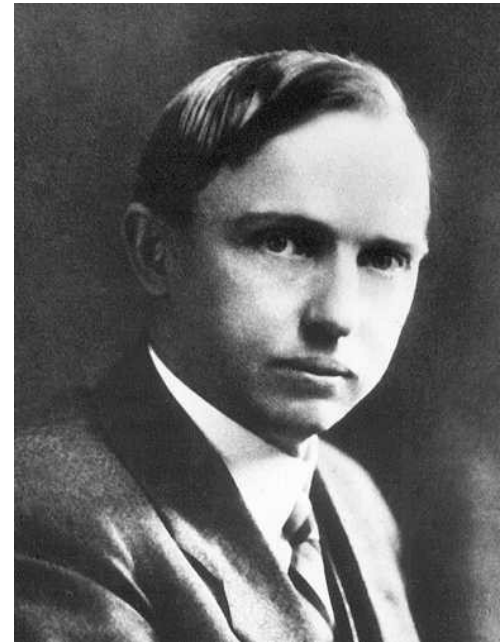
Layover: Globular Clusters

- Large balls of stars.
- Contain anywhere from 100,000 to 3 million stars.
- They are distributed spherically in the Milky Way. Shapley guessed (correctly) that the center of the Milky Way = the center of the GC distribution.

Great Debate of 1920

- Took place at the Museum of Natural History in Washington, DC, between Shapley & Curtis, on April 26.

- Topic: "The Scale of the Universe".

Great Debate of 1920

- Shapley argued that:
  - The Milky Way was large, 100 kpc across, with the Sun far from the center.
  - Other spiral nebulae were inside it.
- Curtis argued that:
  - The Milky Way was small, with the Sun close to the center.
  - Other spiral nebulae were separate galaxies, like the Milky Way.

Who was right?

- **A**: Shapley
- **B**: Curtis

Irony of the Great Debate

- Both were right in their revolutionary ideas, and both were wrong in their conservative believes.

- If the Milky Way was so enormous as Shapley found, and other spiral nebulae were similar to the Milky Way, then they should be at such large distances, which seem totally unreasonable. So, the Aristotelian prejudice appeared again.

- Now we know that the Milky Way is about 30 kpc across, and the Andromeda galaxy is 780 kpc away from it.

Edwin Hubble (1889 – 1953)

- UofC undergraduate (1910) and graduate student (1917). Worked as a basketball coach at a high school in between.
- Served in both World Wars as a major; got the Legion of Merit.
- In 1919 began his career at Mount Wilson Observatory.

Hubble as Astronomer

- Using *Cepheid variables*, he measured the distance to the Andromeda galaxy and found that it was 200 kpc, thus settling the debate. This distance was later revised to 800 kpc.

- He developed a classification scheme for galaxies, which still has his name.

- Measured redshifts and distances to galaxies, and discovered the *Hubble Law.*

Hubble Law

- Hubble found that most galaxies move away from the Milky Way (have positive redshifts). The recession velocity is *approximately* proportional to the distance to the galaxy.

$$v = H_0 d$$

- H_0 is called the **Hubble constant**, it is the same for all galaxies.

Hubble Constant

- It is measured in km/s per Mpc (km/s/Mpc).
- This is a weird unit:
  - 1 Mpc = 3.086×10^{19} km
  - 1 km/s/Mpc = 3.24×10^{-20} Hz   (Hz = 1/s)

- The best current value:

$$H_0 = 70.1 \pm 1.3 \text{ km/s/Mpc}$$

(from cosmological observations).

Hubble Diagram: Then …
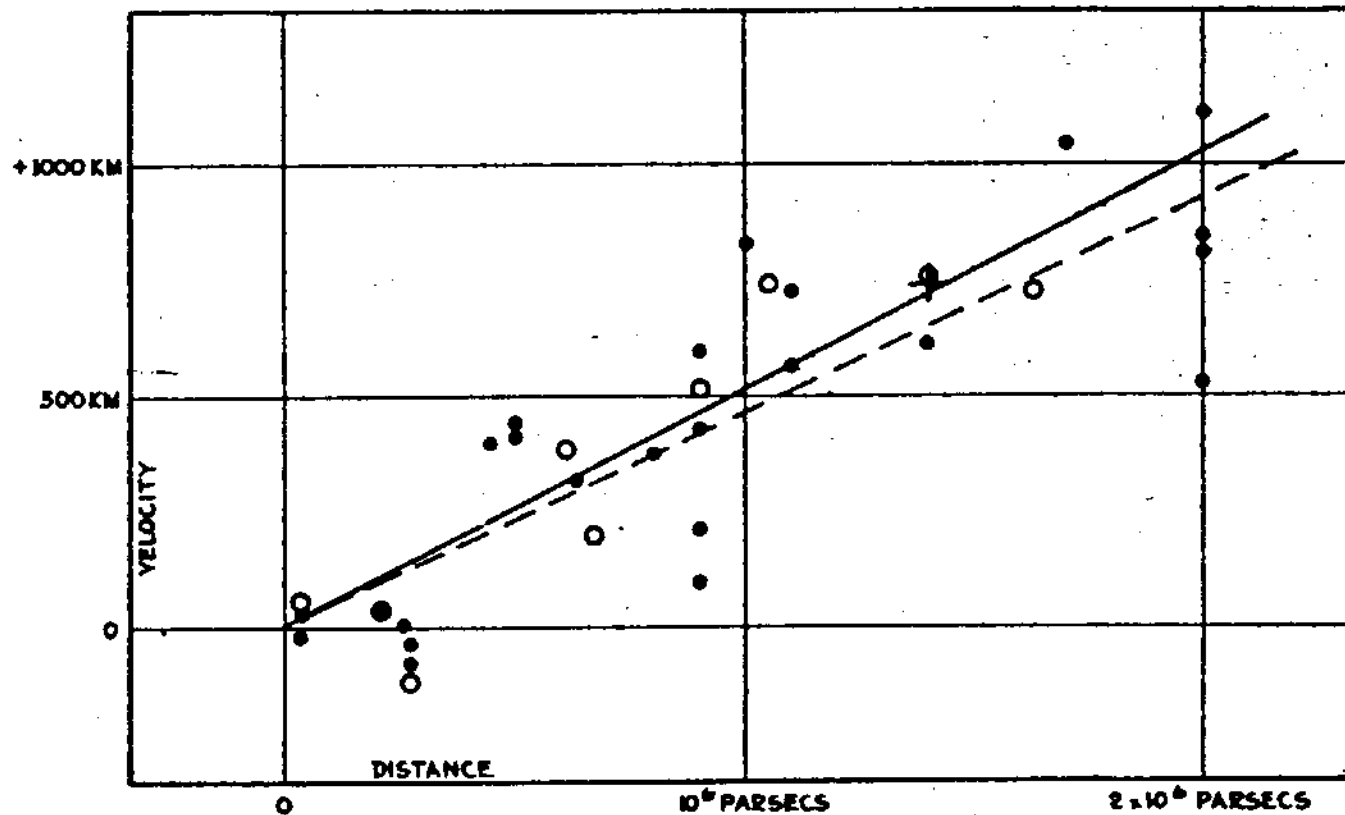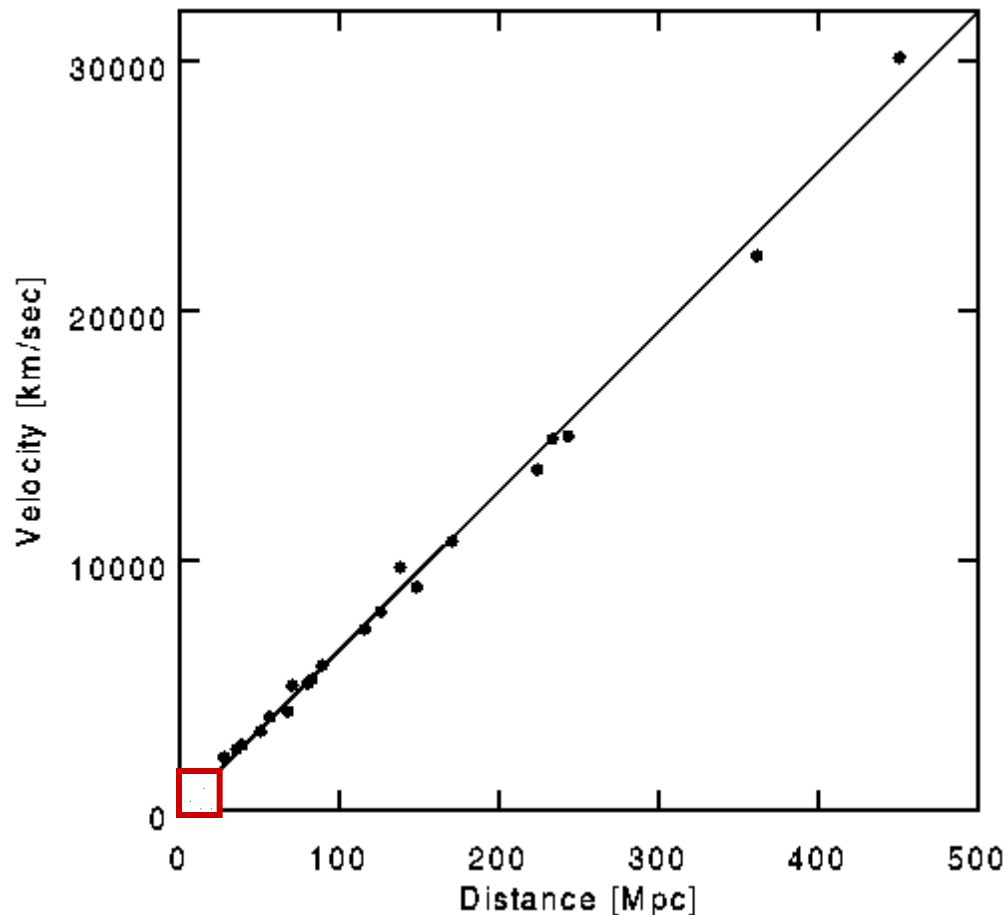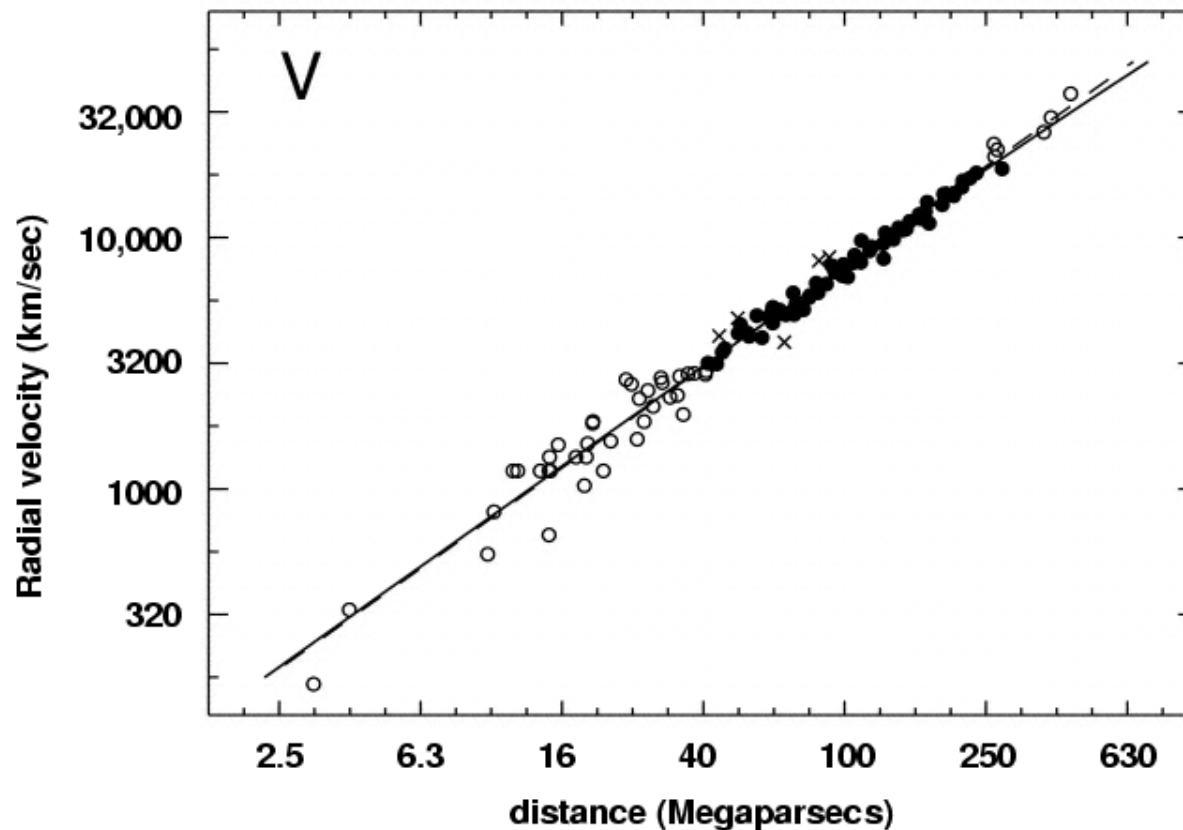

FIGURE 1

Hubble Diagram: … And Now
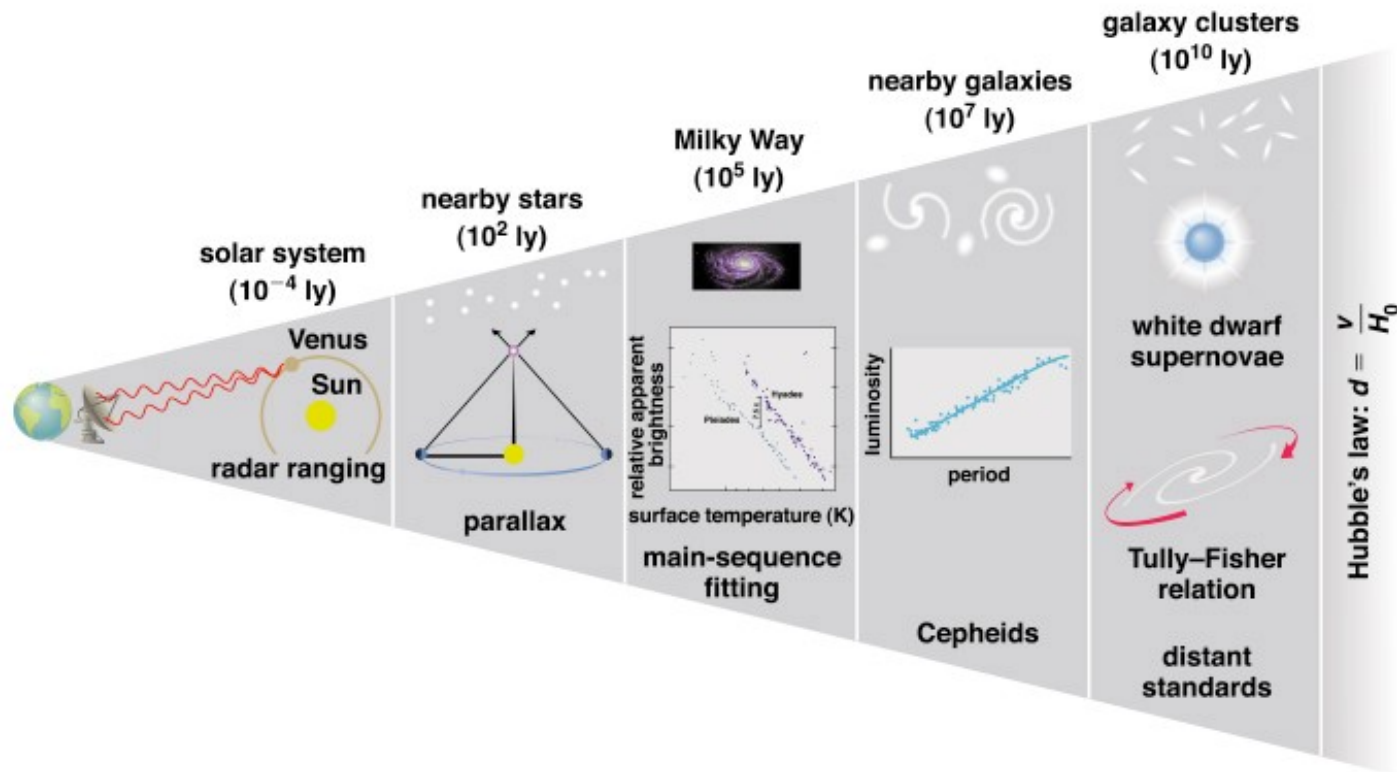
Hubble Diagram: The Best

Hubble diagram for Type Ia SNe

Cosmic Distance Ladder

Distance Ladder At A Glance

Why Do We Need A Ladder?

- To measure distances accurately to remote astronomical objects like other galaxies is still a very difficult task. We do it by using different methods at different distance (like rungs in the ladder), and then trying to tie the rungs together whenever they meet.

- Distances to nearby stars can be measured by the parallax. Beyond that we need to use the *luminosity distance* of a *standard candle.*

Luminosity, Brightness, Distance

- Observed brightness of an astronomical object (apparent magnitude), its luminosity (absolute magnitude), and the distance to the object are related.

$$B = \frac{L}{4\pi D^2}$$

1 AU

2 AU

3 AU
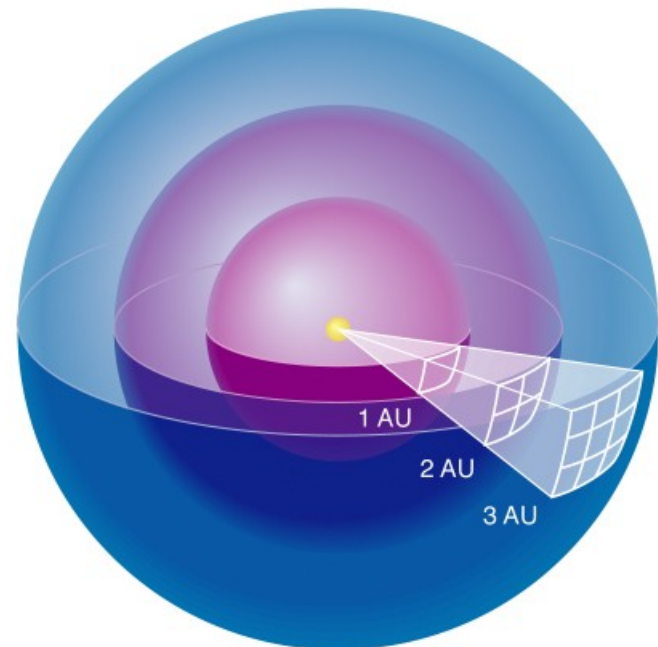
Cepheid Variables

- The best standard candle available to astronomers today is a **Cepheid Variable** star.

- This type of stars change their brightness with a fixed period, and the brighter the star, the longer the period. Thus, by measuring the period of a Cepheid variable, we can determine its luminosity and thus the distance.

- Cepheids allow astronomers to measure distance to about 20 Mpc.

Henrietta Leavitt (1868 – 1921)

- Worked at Harvard College Observatory as a "human computer" since 1893.
- In 1908 - 1912 discovered the *period – luminosity relation* for Cepheids.
- The relation was *calibrated* by Ejnar Hertzsprung in 1913.
- She died of cancer the year Shapley became the Director. Shapley later refused to nominate her for the Nobel Prize, claiming all credit to himself.

SNIa As Standard Candles

- Thermonuclear supernovae can also be used as standard candles, because they have a *luminosity – decay rate relation* (similar to Cepheids).
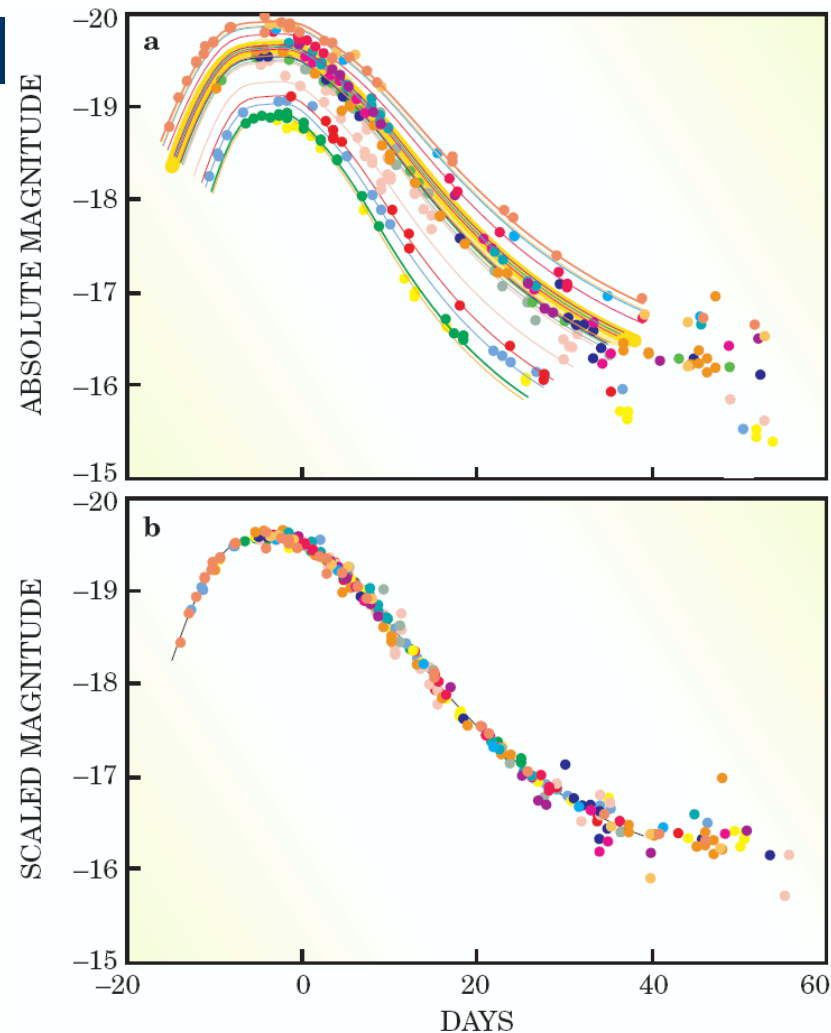
SNIa: Hunting for the Dark Energy